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Application of the Aluminum
Cell for Voltage
Regulation of Alternators

Electrical Engineering

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APPLICATION OF THE ALUMINIUM CELL
FOR
VOLTAGE REGULATION OF ALTERNATORS

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BY

FRANK LOUIS COOK

THESIS
FOR THE
DEGREE OF BACHELOR OF SCIENCE
IN
ELECTRICAL ENGINEERING

COLLEGE OF ENGINEERING
UNIVERSITY OF ILLINOIS

PRESENTED JUNE 1908

14109 Craig

UNIVERSITY OF ILLINOIS

June 1, 1908

THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

FRANK LOUIS COOK

ENTITLED APPLICATION OF ALUMINUM CELL FOR VOLTAGE REGULATION OF

ALTERNATORS

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Bachelor of Science in Electrical Engineering

Elbery B. Paine

Instructor in Charge.

APPROVED:

Morgan Brooks

HEAD OF DEPARTMENT OF Electrical Engineering

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One familiar with the operation of the modern power plant, which supplies all or a portion of its power to incandescent lighting, realizes fully the importance of good voltage regulation for this work. The value of good regulation in its relation to the life of an incandescent lamp is shown by tests which have been made with ordinary carbon filament lamps. It has been found that with the voltage 1% above normal, the life of the lamp is decreased 20%, while its candle power is increased only 6% above normal. Should the potential be raised 5% above normal, the consequent reduction in the life of the lamp would be 64%, while the increase of candle power would be only 33%. Again reducing the voltage 2% below normal increases the life 50%, while the candle power is in turn, lowered 11%.

It is evident from this data that a slight increase above normal voltage is very detrimental to the life of the incandescent lamp, while a slight reduction in potential materially lowers the candle power. On this account a number of machines have been devised for automatically maintaining the voltage at a definite desired value. It will be apparent, however, that to maintain the close regulation desired, namely, less than 1%, instruments must be delicately constructed, and finely adjusted, these conditions resulting generally in the compulsory design of a machine having numerous and sensitive parts, which may become deranged, rendering the use of the regulator uncertain and even unsafe.

Of the numerous voltage regulators which have been devised, the Tyrell regulator manufactured by the General Electric



Co. has probably survived best, the stringent requirements exacted from such a machine. In principle this instrument is similar to the old-fashioned wheel regulator, operated by hand, in that it controls the generator voltage by changing the value of the current in the exciting unit, which furnishes power to energise the fields of the alternator. This operation is performed automatically by means of magnets whose actions close shunt circuits through the manipulation of polarized relays energized by the balance of power between generator and exciter shunts.

The Tyrell regulator is the best of its type, yet it has not reached a state of perfection, but still has a number of defects which occasionally cause serious trouble. Among its bad features we may say that it has some delicate pieces, although these have been reduced to a minimum and it has a number of moving parts, which always means wear and the eventual breaking down of these members. Further, the magnets used in the regulator cause the electric circuits to be made and broken almost incessantly, resulting in worn out contacts due to sparking effect. Consequently the contacts, in time, catch and bind, often causing the generator voltage to rise considerably above normal value thus endangering any lamps in the circuit. The delicate adjustment of the parts, in turn, requires that the support for this type of regulator be rigid, and at the same time free from vibrations always present in power stations.

With these points in mind, the writer has endeavored to develop an instrument which has none of the undesirable features

of the present commercial machine. In the apparatus subsequently described in this paper we can say that there are no delicate mechanisms, no moving parts, no sparking contacts, no wear on bearings, it is unaffected by vibration, and further the tests which we have made of the equipment would seem to indicate that the regulation is quite as good as instruments now used in power plant work.

For a number of the ideas and principles in the construction of the apparatus the writer is greatly indebted to Mr. Fred D. Smith - Illinois '05, - who has been an earnest adviser and co-worker in its subsequent development.

We are aware that in all generators there is more or less residual magnetism which, in D.C. machines may be built up, causing, in time, full field excitation. Such generators are known as self excited machines. The ordinary alternator requires a separate generator, which has this self exciting principle, to furnish the energy for its fields. Under constant speed relations between the generator and its exciter, the generator voltage varies directly with the flux in the exciter fields, and by varying this flux we may obtain any desired generator voltage within the limits of the machine outputs. To cause such variation of flux, another coil may be wound on the exciter field in opposition to the main field winding, so that passage of current through this additional coil reduces the flux in the exciter lowering its terminal voltage and thereby affecting the voltage of the generator which it excites.

In the action of this new type of regulator, two trans-

formers are used, connected in parallel across the generator bus-bars with their primaries in opposition and secondaries in series. It is evident that if these two transformers are connected alike, the resultant potential across their secondaries will be zero. Should they be slightly different, one generating, say 110 volts and the other 100 volts, the resultant potential will be $110 - 100$ or 10 volts.

With this fact in mind, the action of the regulator can be explained, the operation being made clear by reference to diagram #1. The generator is assumed to be at normal voltage under excitation from the exciter. Under these conditions there is no resultant potential across the transformer secondaries A.B. Suppose the voltage changes. The transformers are so constructed that their action is neutral only at normal voltage, consequently under the new condition there is a potential across the secondaries. This causes an alternating current to flow which is passed through some form of rectifying device which changes the current to D.C., and this current passing through the opposition field, of the exciter, varies its voltage, which, in turn, changes the flux in the alternator field, bringing the terminal voltage of the alternator back to the normal value.

The difficult features of the apparatus, are proper transformers and suitable rectifiers. In the study of rectifiers for this work the mercury arc rectifier was discarded as it does not readily operate below fifty volts, and is, in itself, nearly as complicated as the Tyrell regulator, and thus would defeat the main object of this research. For this reason attention was

turned to the developement of the aluminum cell for rectifying the alternating current. Considerable time was spent in testing this type of cell before anything could be done with the application proposed for it. In the year 1856, a physicist by the name of Buff first discovered the property which is possessed by aluminium, when dipped in a salt solution, of allowing a free flow of current in one direction, but of stopping the flow in an opposite direction. Ducretet, in 1876, utilized this property for constructing an alternating current rectifier, but it was not until 1899 that exhaustive tests of this characteristic of aluminium were made. These experiments were carried out by Albert Nodon of the College de France, and he named the apparatus with which he worked, the Electric Valve. This valve effect is, in general, common to any metal dipped in an electrolyte and subjected to a definite difference of potential. The effect may be obtained to a slight degree with ordinary water. In practice, however, the choice of the electrolyte is important in the operation of the valve. The elements magnesium and aluminium admit of the valve effect being obtained under high difference of potential, while lead and mercury produce this phenomena under a low potential difference. Thus the high potential elements may be used as cathodes and the low potential metals as anodes. The action of the cell seems to have no effect on the anodes, however.

The combination of aluminium and lead with an electrolyte of neutral ammonium phosphate seemed to give the best results in the tests which have been made in this investigation.

Solutions of alum and potassium phosphate were also tried, using, in turn, anodes of carbon, iron, and amalgamated zinc, but the result in these cases was precipitation, leakage, or chemical reaction on the electrodes. Even under the best conditions it was found that the leakage of alternating current occurred when the current passing through the cell raised its temperature above 70° F.

Considerable difficulty was experienced in obtaining the proper size of cathode to prevent voltage breaking down and yet limit the temperature rise. The first cells used were constructed of nine inch gravity jars, lined inside with lead as anodes. The aluminium plate was suspended in the center of the jar. This plate was 6" X 4" X 1/4". It was found necessary to materially reduce the size of the cathode, however, and the improved cells use plates having about 10 sq. cm. area, which is equivalent to about 2 sq. cm. per ampere.

There has been much discussion as to what causes the peculiar action of the electric valve, and several theories have been advanced. Ducretet, and a number of the early investigators maintained that it was the high resistance of the film formed on the aluminium plate which prevented the passage of the negative half of the A.C. wave. Monsieur Nodon, in his work, came to the conclusion that the action was due to capacity effect, but recent experiments carried out by Dr. K. Norden indicate that the operation is an electro-chemical one. In an article written for the Electrical World of October 26, 1901, he states that the action of the electrolytic valve appears to be that a

thin film of normal aluminium hydroxide, $(Al_2(OH)_6)$, forms on the plate, which when the aluminium is the anode, and the potential below a certain value will not allow current to pass from the aluminium to the lead plate, but, when the direction of current is reversed, the film becomes of low resistance and allows current to pass from lead to aluminium. As this film is practically a dielectric the current flow towards the lead is greatly impeded, although not completely stopped, but as the film is rapidly soluble in its electrolyte the current flow toward the aluminium plate which builds up the film is practically continuous, resulting in the unidirectional current.

Oscillograph records of this valve proved very interesting and instructive. The common type of oscillograph such as the General Electric Company manufacture is not very suitable for this work as an alternating current is necessary for the operation of the synchronous motor in period with the mirror vibrations, while the current from the aluminium cell is pulsating. For this reason a more simple apparatus was set up, which, although primitive in design, gave excellent results. A rough sketch of this oscillograph is shown in diagram #2. Two coils are mounted on a bi-polar magnet, A A, whose pole tips are separated about a quarter of an inch. Between these poles is passed a loop of thin iron wire, B B, supported at one end by the insulating plug, C, by means of which the tension in the iron wire, is also regulated. Directly in the magnetic field, and held by the tension in the iron wire, is placed a small galvanometer mirror, D. In compliance with the laws of magnetic fields

around conductors, when direct current is sent through the magnet coils and alternating current is passed through the iron wire loop, there will be a rapid vibration of the iron wires corresponding to the instantaneous values of the alternating current. If now a small beam of light be thrown on the mirror, the reflection which it will cast on a screen will be a vertical line, as the mirror vibrates about a horizontal axis. If in place of a screen, another mirror is substituted, rapidly rotating about a perpendicular axis, the vertical line mentioned above will be drawn out, so that the reflection from the rotating mirror will give a wave form.

Passage of alternating current through this oscillograph produces a curve similar to that shown in diagram #3. When an aluminium cell is connected in series with the vibrating coil of the oscillograph, the resulting curve is similar to that shown in diagram #4. This shows that the lower half of the wave is completely cut off. In this case the resulting current is merely a pulsating one.

A method has been devised, however, which enables us to utilize the lower half of the wave also, and thus double the amount of current which may be obtained from the valves. This arrangement is credited to a German by the name of Graf, and is known as the Wheatstone bridge method. In this scheme four cells are required which are set up as shown in plate #5. Let us assume that at some definite instant a current enters at A. Remembering that passage is allowed only from lead to aluminium, we see that the current may pass through only cell #1, then

across the load in the direction of the arrow, and out through cell #4. The next instant current enters through cell #3 at B, passes across the load in the same direction as before and out through cell #2. Thus both halves of the A.C. wave have been utilized, giving a direct current across the load in the direction of the arrow. The oscillograph record is then similar to that shown in diagram #6. With two and three phase currents we get an even better D.C. resultant, as the tops of the waves approach more nearly a straight line as illustrated by the diagrams of voltage and current waves on plate #7. The two phase arrangement requires eight cells, as represented in plate #8, while the three phase connections use six cells.

In the use of the electric valve the I^2R heating losses give some trouble, but this is remedied, in a measure, by means of water or air cooling devices. Heat is liberated at the aluminium electrode. To keep this cathode cool it is sometimes made in the shape of a hollow tube so that water may be passed through it to keep the temperature down. Under ordinary conditions the Nodon valve will give an efficiency of about 70%. Cells constructed in our laboratory have had an efficiency as high as 81%, but only for a short time, however, as the cells were not constructed for use with large currents and the subsequent heating produced leakage effects which lowered the efficiency perceptibly. The cells operate on any voltage up to about one hundred fifty volts, but beyond this value the hydroxide film crystallizes and the valve action fails. Experiments carried out by Nodon show that the cells have a power-factor of more than

than 90%. In the apparatus constructed in the laboratory the valve effect is complete up to the range of the cell (about four amperes) after which alternating current leaks through. This leakage increases with the load as may be seen by reference to curve #9.

We may now turn our attention to the transformers which supply the power to the cells. For the purpose of illustration we assumed one coil smaller than the other in order to obtain a difference of potential across the secondaries. It is clear, however, that when the generator is at normal voltage we do not wish any current to flow through the secondary coils as the voltage of the generator is then what we desire. To obtain this condition of like output at normal voltage, but a differing ratio of transformation under a change of potential, one of the transformers was constructed to give poor regulation. Such a transformer may be constructed by arranging for over-saturation of the iron core or by increasing the air gap between the coil and its core, thus producing magnetic leakage. Both schemes were tried individually and collectively before a suitable transformer was obtained. Although engineers are conversant on the principles that go to make up a "good" regulation transformer there is no definite data at hand to guide the experimenter in building a poor regulation device. The transformer desired was obtained after a series of experiments, using a "cut and try" process, involving the construction of three separate transformers before the proper conditions were found. In the final design the principle of an air gap was completely discarded and the apparatus

relies solely on the idea of oversaturated cores.

To enable one to understand fully this principle a magnetization curve has been drawn, plate #10, This curve is plotted with ampere-turns as abscissae, and flux, or lines of force, as ordinates, Since the number of turns in a transformer remains constant we may assume that the horizontal axis represents current values. Beginning at zero, examination of the curve shows that a small current gives a large value of flux, but after the current reaches a certain value the ratio of the flux to the current changes, so that a great increase of current varies the flux in the iron but little. Under these conditions the iron is said to be saturated. The sudden bend in the curve is termed the "knee", and it is just below this point that the commercial transformer is made to operate. Now, should we build a transformer whose working conditions are just above the "knee" it is evident that we have the qualities desired in the "opposition transformer" previously mentioned. The transformer used is shown in sketch #11, and is designed for a normal primary pressure of one hundred ten volts. This transformer has concentric primary and secondary windings with a laminated wrought iron core and a closed magnetic circuit. The ratio of transformation is two to one, using seventeen hundred turns on the primary to produce over-saturation in the core. Sketch #12 shows a number of transformer arrangements which were tested and discarded due to dispersion effects.

A diagram of the wiring connections used for the regulator apparatus is given in sketch #13 which differs from plate #1

only in that it gives more detail. The exciter was separately driven so that the speed of the generator would not affect it. After the exciter had brought its own field to full excitation, the A.C. generator was started up and current taken from the exciter sufficient to give the generator a terminal pressure of one hundred ten volts. At this point there was no resultant voltage in the secondary circuit of the transformers. The A.C. generator was then speeded up, resulting in a rise of the A.C. terminal voltage which, in turn, produced a difference of pressure in the transformer secondaries, so that when the switch A was closed, A.C. passed into the cells, where it was rectified, producing a demagnetizing effect on the exciter by means of the opposition coil on its field. This consequently reduced the A.C. generator excitation, causing the terminal voltage to become normal, although the speed of the machine was still above its rated value. These first trials indicated that the principle of operation is a success, although the size of the machines which it was found necessary to use in the laboratory was somewhat of an impediment to close regulation. The chief difficulty was the lack of a good exciter, and to overcome this trouble another machine was added which might be termed an exciter relay. Its purpose is shown in plate #14. The rectified current instead of passing through the demagnetizing coil of the exciter, is used to energize the fields of the D.C. relay, whose output, cut down by means of suitable resistance, acts on the exciter to decrease its flux. There is no change in the rest of the apparatus.

Operation under these conditions gives excellent results,

as may be noted by reference to the data and calculations obtained. For the purpose of securing generator speed readings at the same time as its terminal pressure, a tachometer was belted to the shaft of the A.C. machine and the tachometer voltage read. From these voltages the speed of the generator was found since the tachometer voltage varies with the speed. The calibration curve of the tachometer used in the work is shown in diagram #15.

Tests were made on the A.C. generator with three different values of terminal pressure, and for each determination the speed of the machine was varied between the range of 1375 to 1525 R.P.M. In all these cases the regulation was maintained at the fixed value by the automatic regulation of the regulating apparatus. In order to determine what the rise in voltage would have been without the regulating device, the generator was afterward brought up to the same speeds, and the terminal voltage read, and found to correspond to a change of more than fifteen volts, indicating that the control was efficient over a voltage variation of about 13% of normal pressure. It was found, however, that when the speed of the machine was changed quickly from 1375 to 1525 R.P.M., the regulator was not as rapid in response, but took probably a second to adjust the voltage. This slight sluggishness was attributed to the fact that there was such a great amount of iron in the magnetic circuit as to impede the action somewhat, since we have in all, three exciter fields, and one generator field, and two transformer cores. The equipment in commercial practice will require but a single exciter and the generator field, thus allowing more rapid response.

Under load conditions the voltage at the point of distribution will drop as the load comes on, due to the IR loss in the feeders, and it is customary for the station attendant to raise the generator voltage a corresponding amount so that the compensating voltmeter will indicate normal voltage at the point of distribution. This operation is provided for automatically in the regulating device, as shown in diagram #17, where a series transformer is placed in circuit, with its secondary in opposition with the rectifier transformers. The pressure in this series transformer varies directly as the current on the generator bus-bars, with the result that it assists the exciter field, allowing the generator to rise to a potential sufficient to maintain normal voltage at the point of distribution.

Reference to diagram #16 will show the degree of accuracy of the regulator which indicates a variation of about 1% maximum.

TEST TO DETERMINE EFFICIENCY AND LEAKAGE EFFECT OF VALVE
RECTIFYING CELLS

4 Cells,- Wheatstone connection

IMPRESSED RESULTANT

A.C.	D.C.
------	------

0.50	0.50
------	------

0.87	0.75
------	------

1.20	1.00
------	------

1.50	1.25
------	------

1.695	1.40
-------	------

2.075	1.70
-------	------

2.45	2.00
------	------

2.75	2.25
------	------

3.35	2.65
------	------

4.12	3.25
------	------

5.47	4.10
------	------

7.00	4.80
------	------

Incandescent lamp load
used for variation in range of
current.

Test of short duration,
slight heating

VOLTAGE RATES OF VARIOUS COILS OF THE POOR REGULATION TRANSFORMER

Rheostat Out - - - - - Full Iron Core

Primary	Coil #1	Coil #2	Coil #3	Coil #4	Coil #5
114.5	92	38	37	19	18.5
		130			
			165		
				181	
					200

Rheostat In - - - - - Full Iron Core

99	83	37	36	18	18
		106			
			146		
				157	
					170

Reversing - Passing source through Secondary - Resistance out

129	115.5				
91.5		116			
70.5			115.5		
63.5				114.0	
57.5					113.5

Resistance In

110	104				
84		104			
67.5			104		
61.5				103.5	
56.5					104

TACHOMETER CALIBRATION IN USE WITH ALTERNATING CURRENT
GENERATOR

Generator Speed	Tachometer Pressure
R.P.M.	Volts
1384	91.00
1400	93.75
1438	96.00
1458	98.50
1520	105.00

Tachometer reading constant during the minute required for obtaining speed reading.

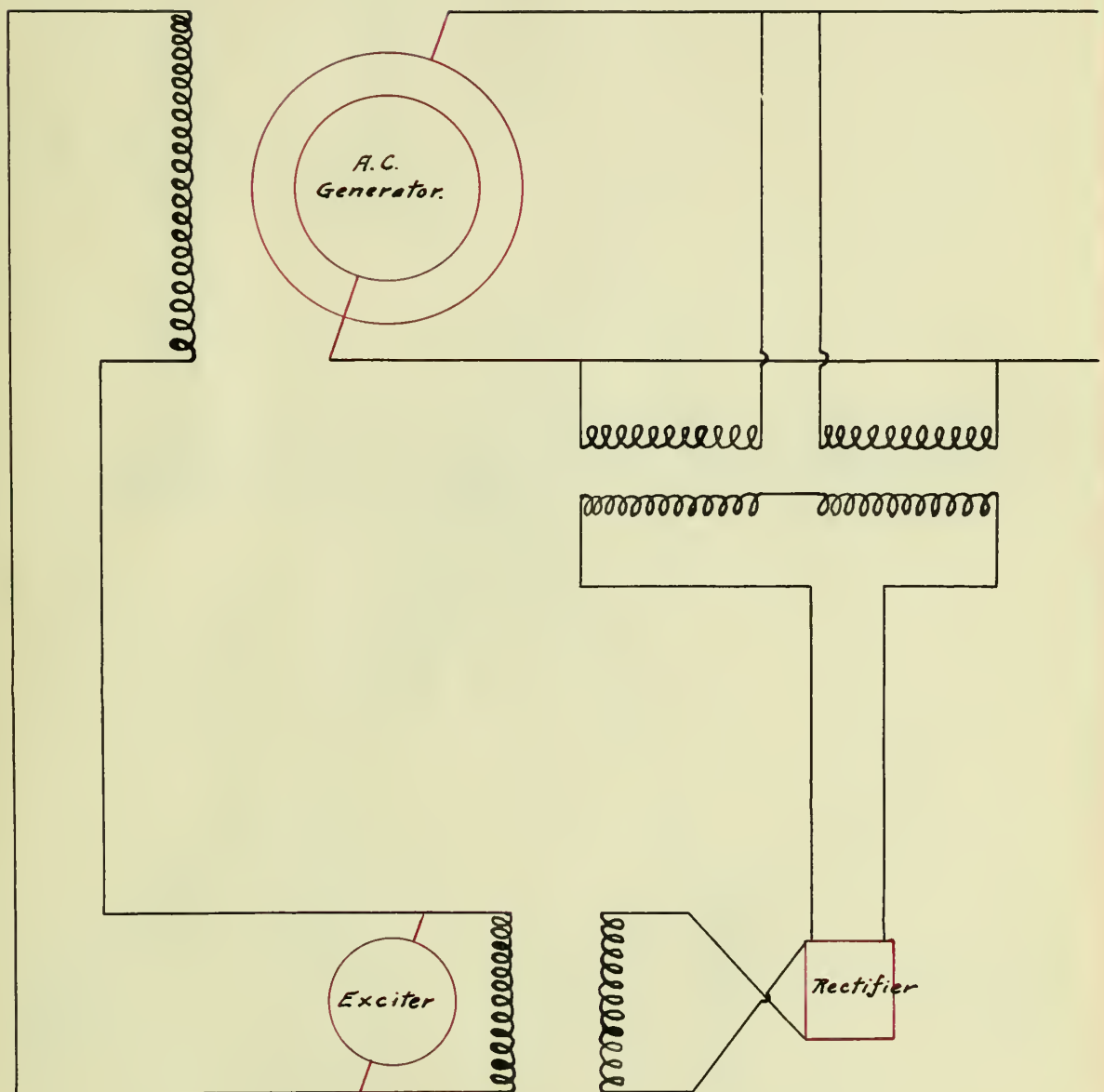
TEST OF REGULATOR SET ON ALTERNATING CURRENT

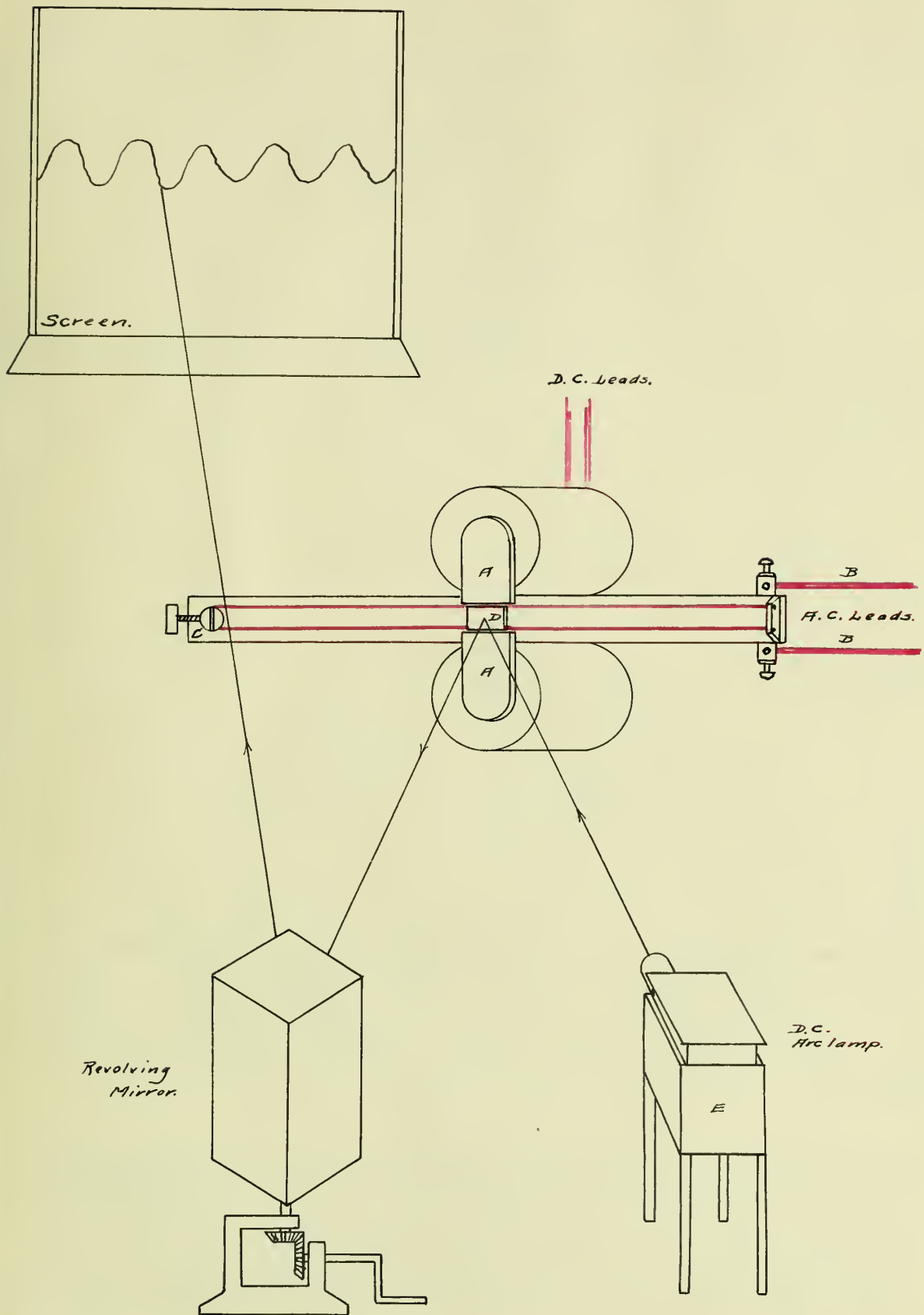
GENERATOR USING BOTH EXCITER AND RELAY

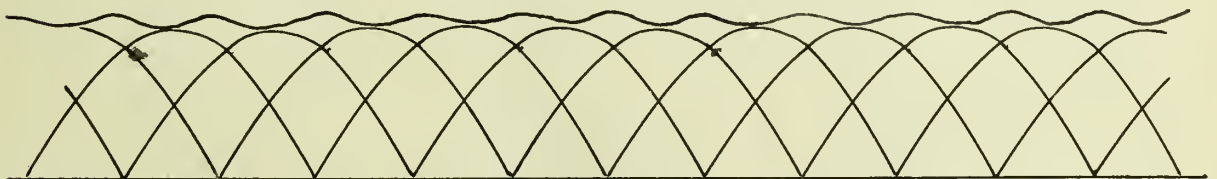
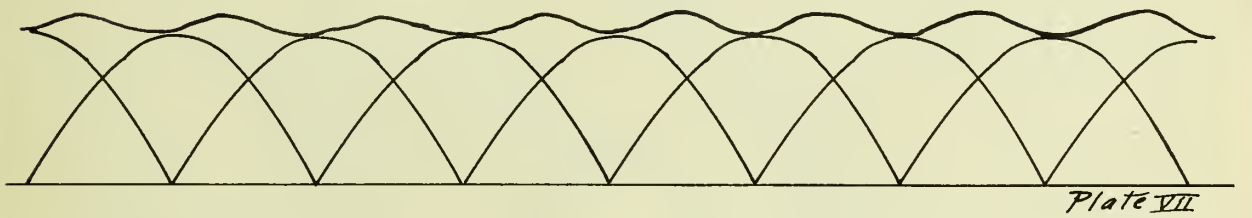
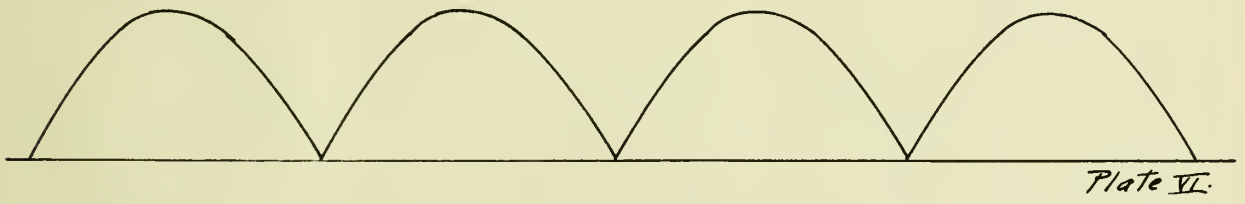
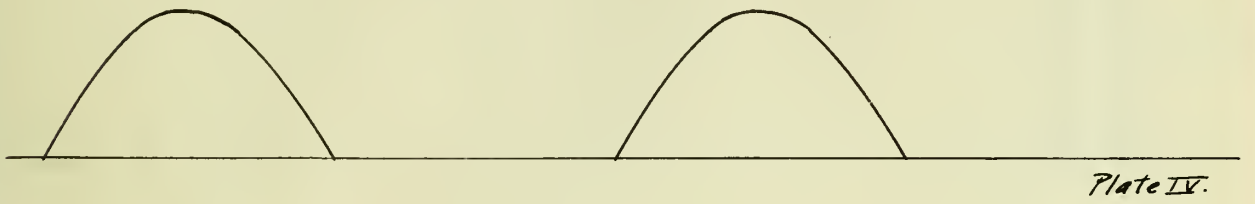
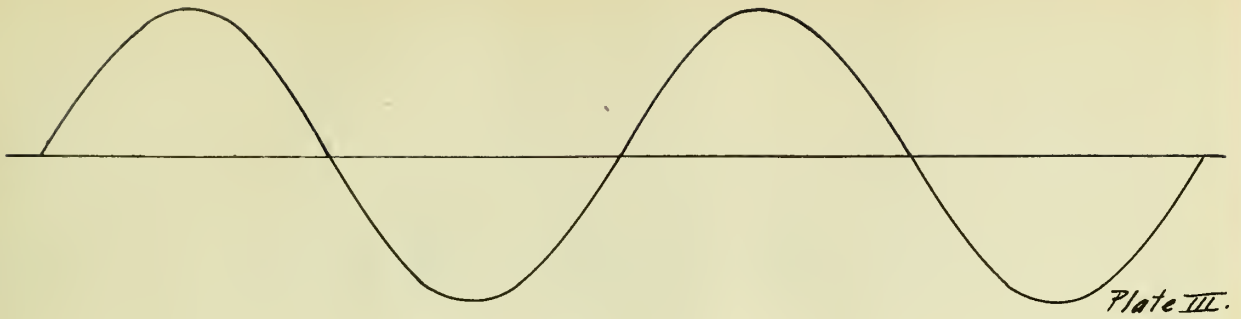
Tacho- meter Voltage	Gener- ator Voltage	Equiv. Voltage Without Regu- lator	Gen. Speed from Tacho- meter Cali- bration	Tacho- meter volt- age	Gen. Volt- age	Equiv. Volt- age Without Regu- lator	Gener- ator Speed from Tachp- meter
91	100.0	99.5	1385	90.5	83.0	83.0	1370
92.5	99.5	101.0	1390	94.0	82.5	85.5	1405
93.5	99.5	102.5	1400	95.5	83.5	86.5	1420
95.0	99.3	104.5	1415	98.5	83.0	89.5	1450
97.0	100.5	105.0	1435	101.5	83.5	91.0	1480
98.0	99.5	106.5	1445	98.5	83.5	89.5	1450
100.0	100.5	109.5	1465	95.0	83.0	86.0	1415
105.0	99.5	115.5	1520	92.5	82.5	84.0	1390
98.0	99.5	106.5	1445	91.5	81.5	83.5	1380
96.0	99.5	105.0	1425				
94.5	99.5	104.0	1410				
93.0	99.5	102.0	1395				
91.0	99.5	99.5	1385				

Excitation of Exciter Increased

90.0	111.5	1365
92.5	111.0	1390
95.0	111.0	1415
98.5	111.0	1450
100.5	110.5	1470
98.5	111.0	1450
95.0	110.5	1415
92.5	111.0	1390
91.0	111.0	1385







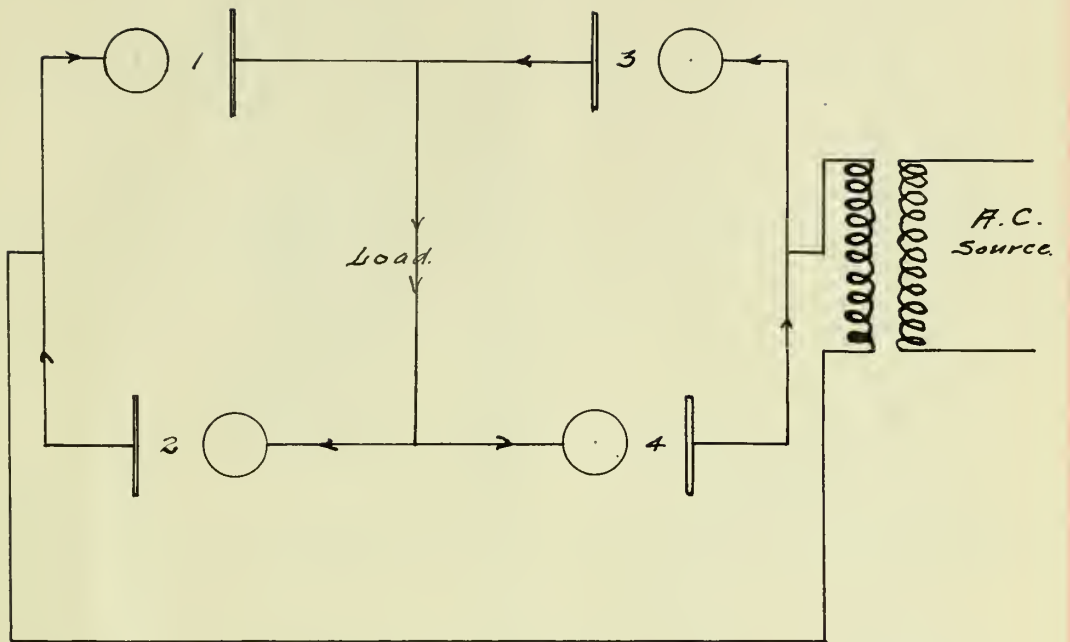


Plate V.

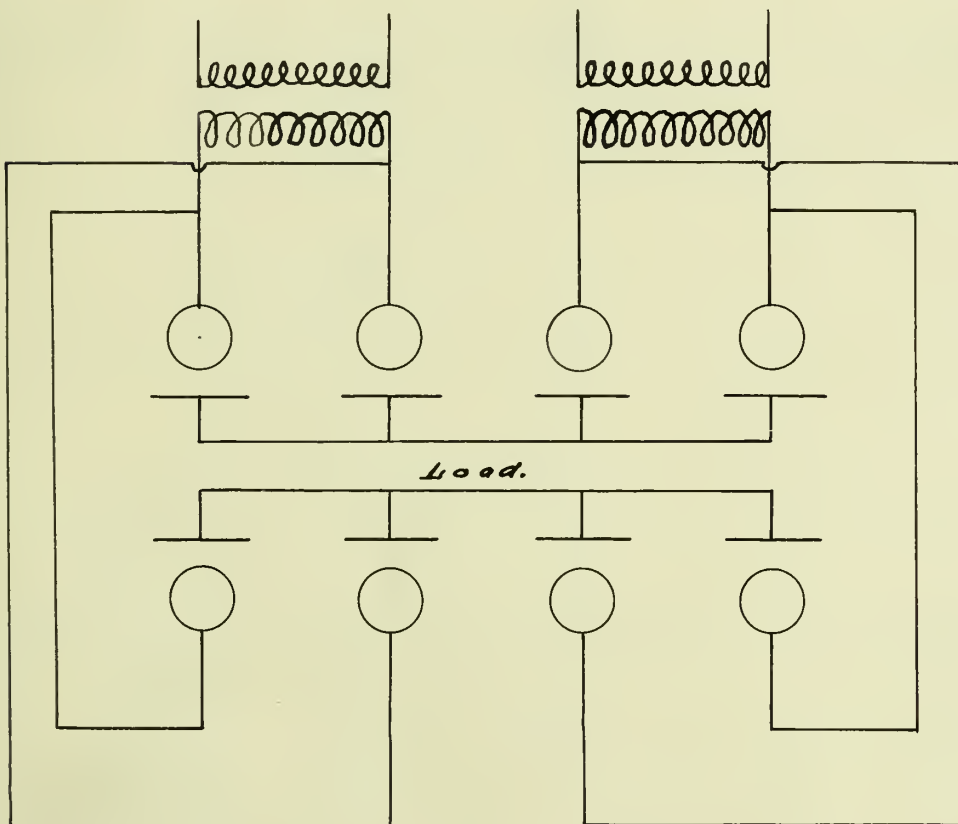


Plate VIII.

Performance
of
Aluminium Cells.

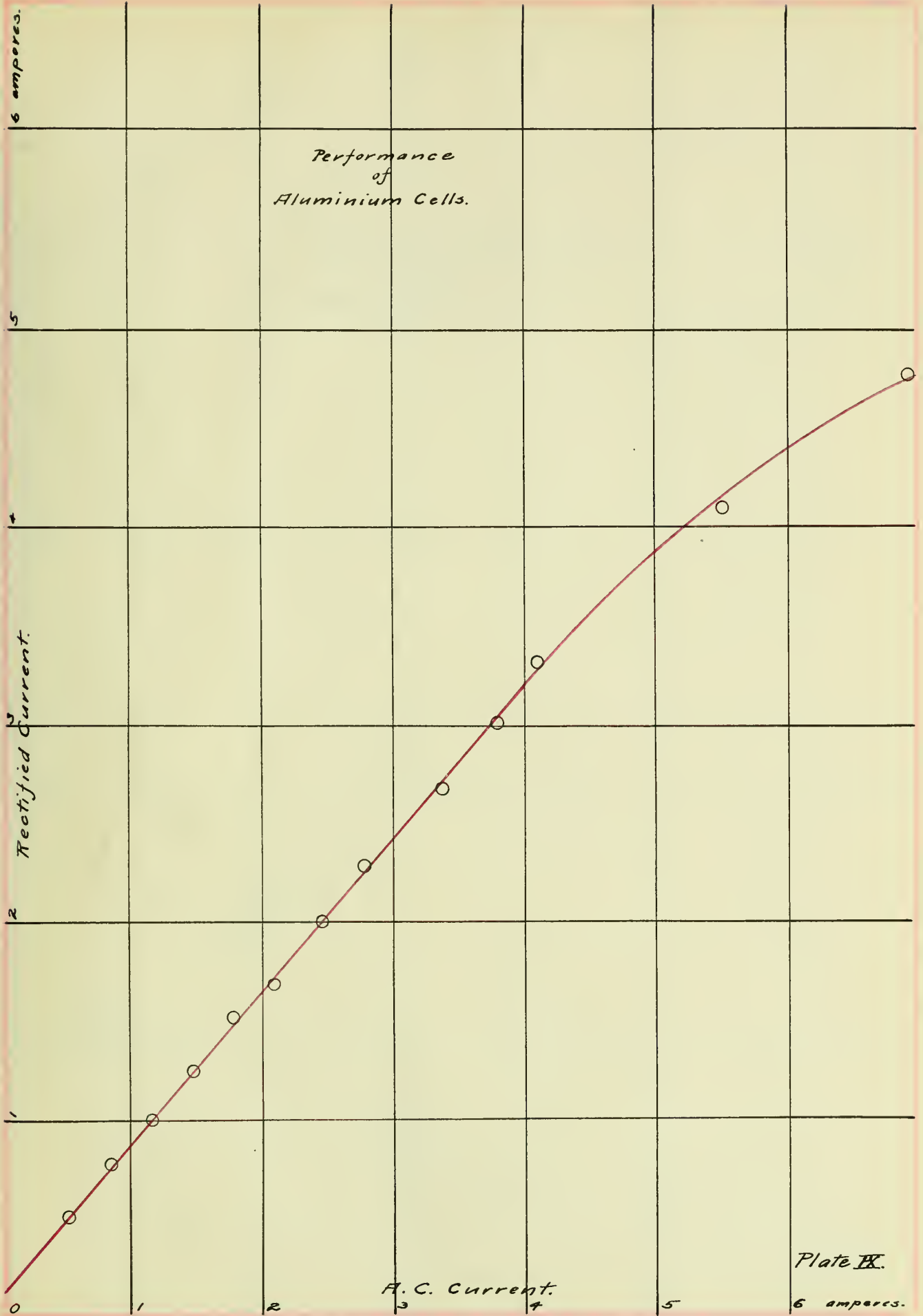
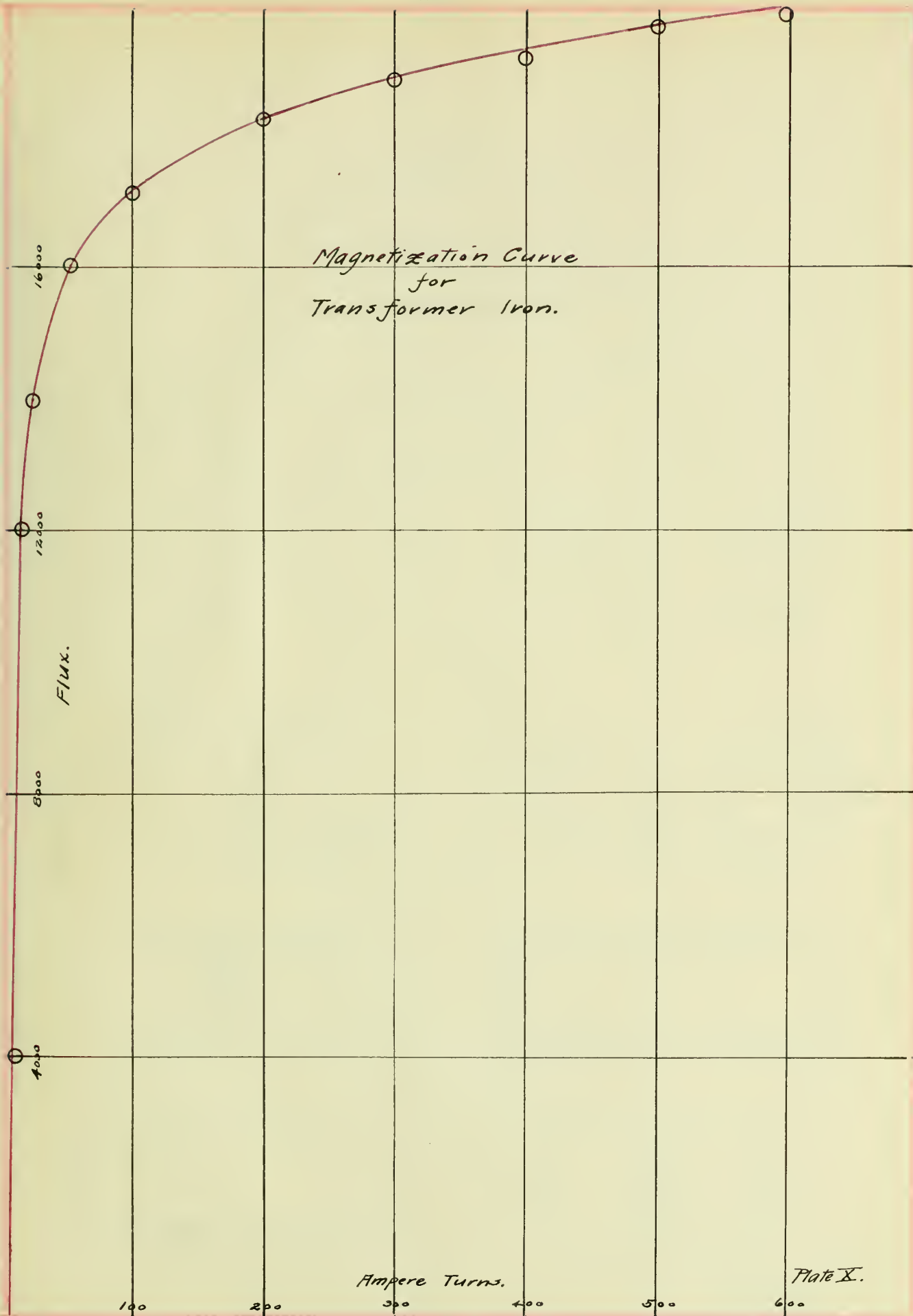
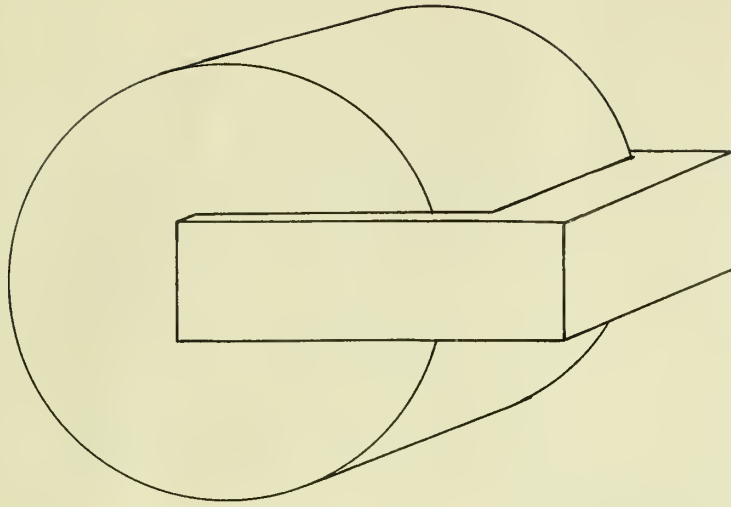
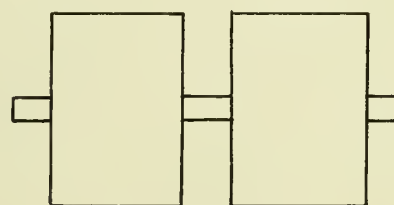
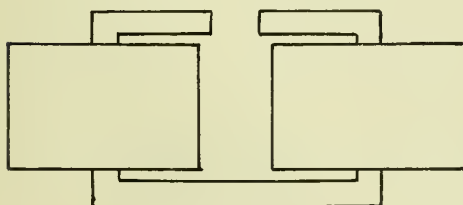
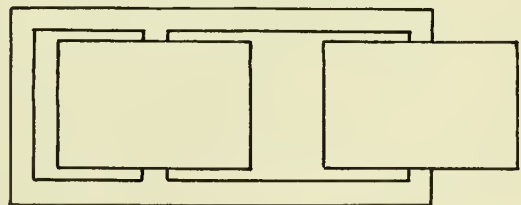
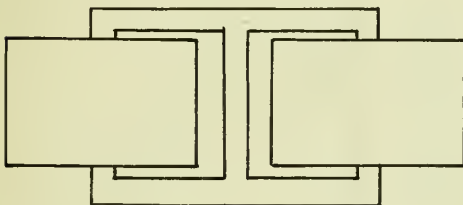
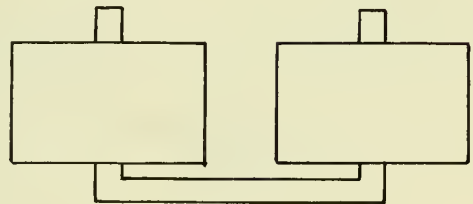
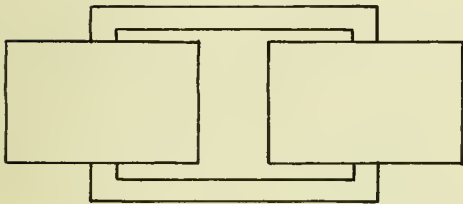


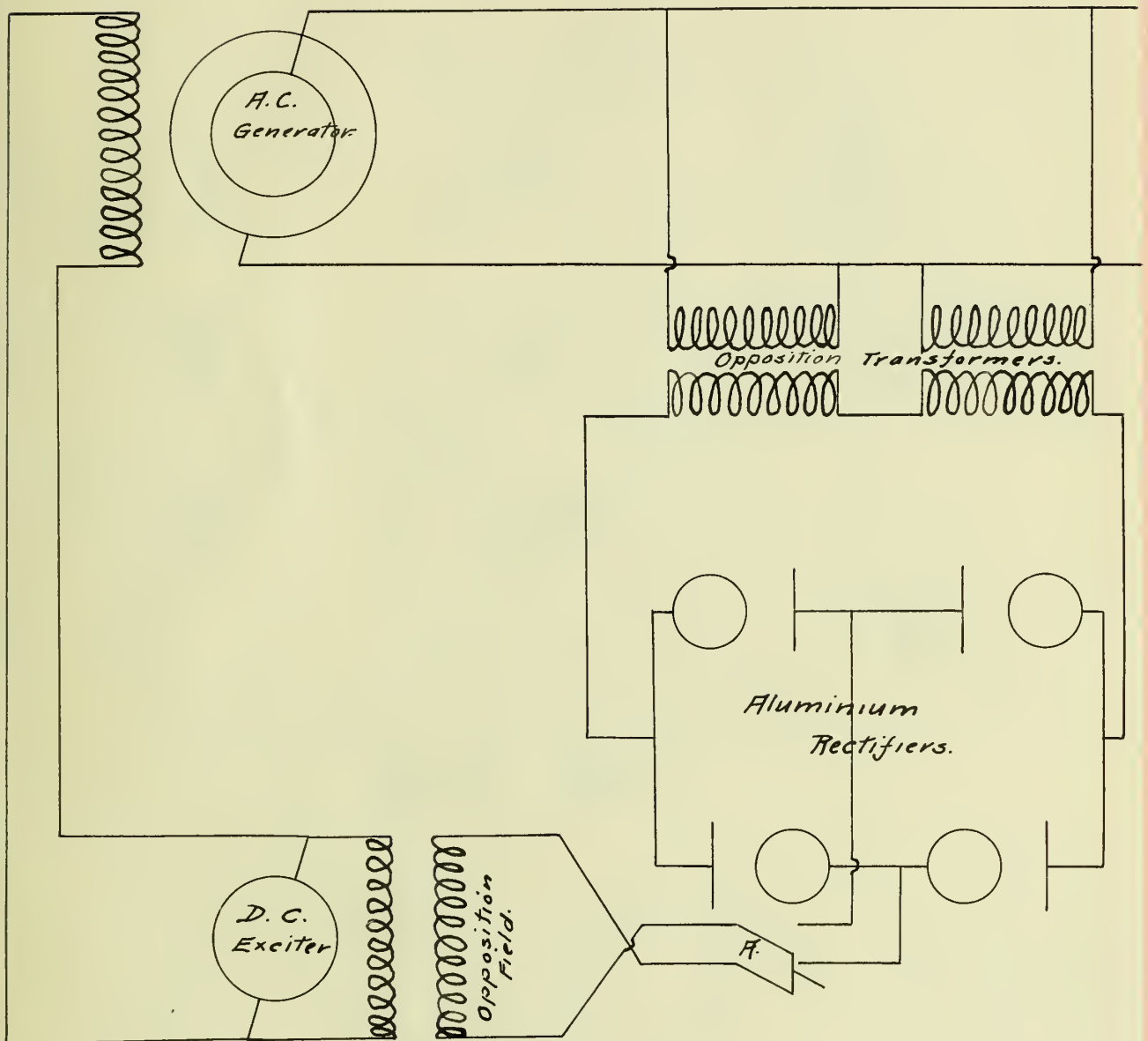
Plate IX.

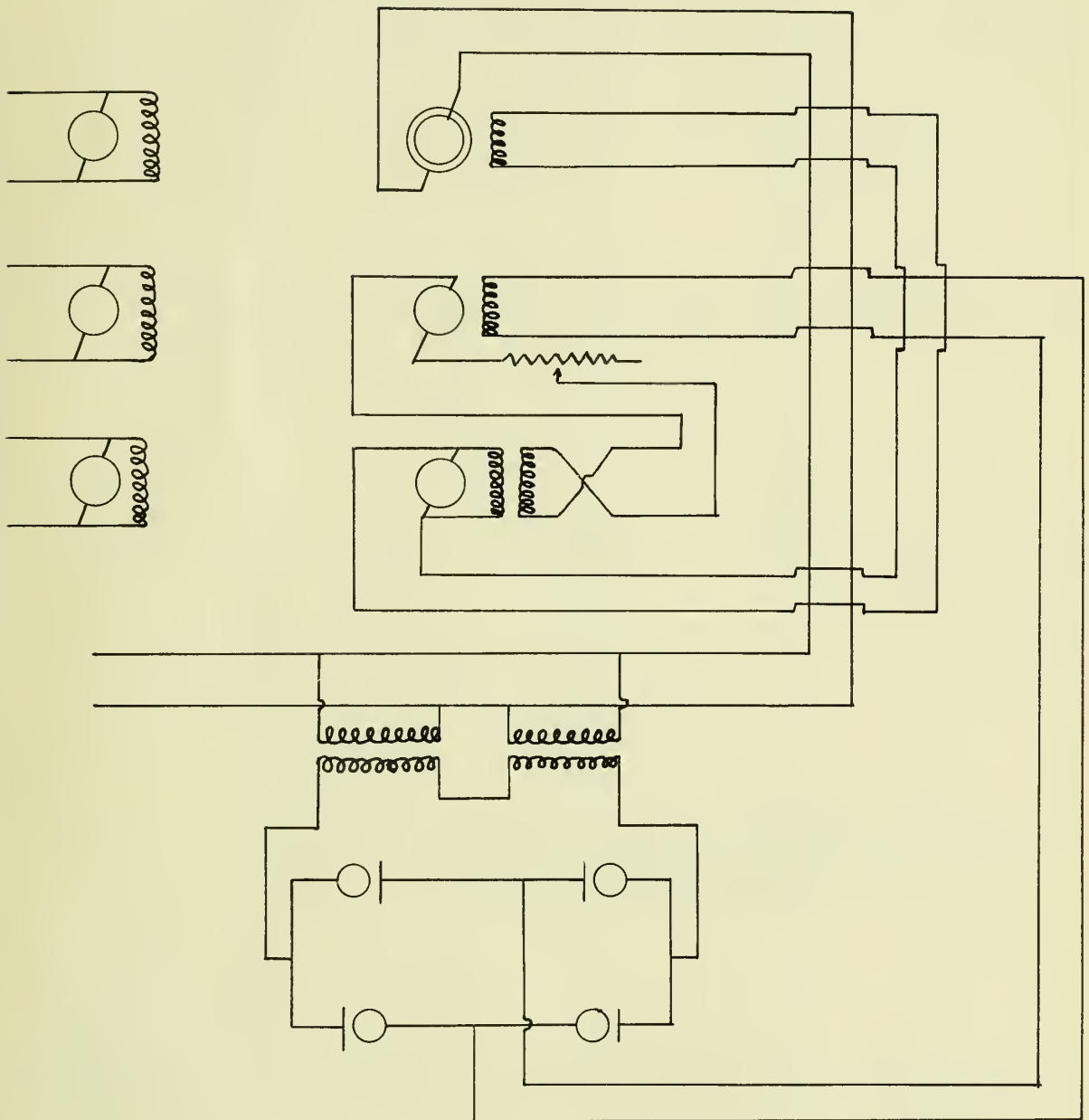
6 amperes.

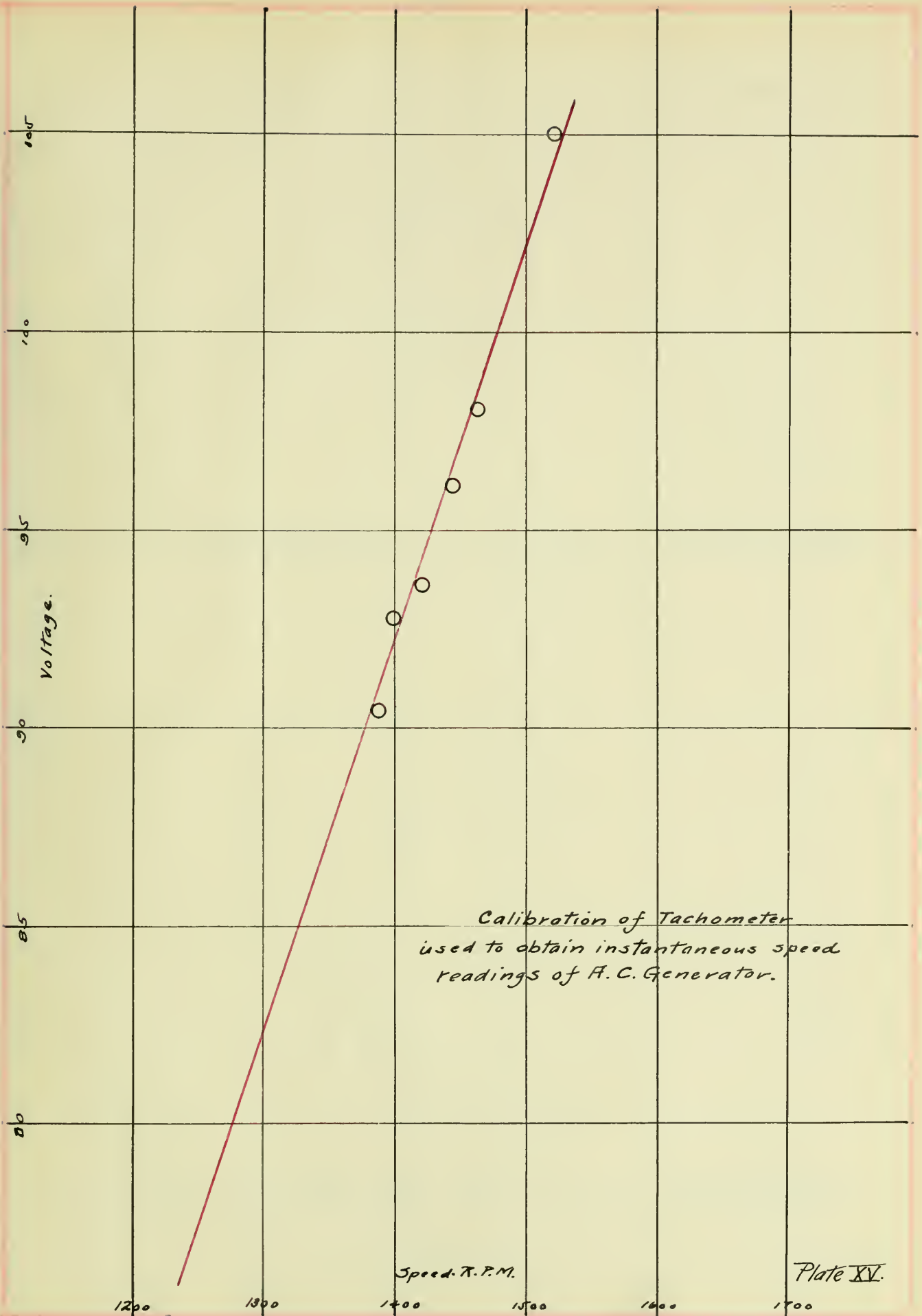
Magnetization Curve
for
Transformer Iron.

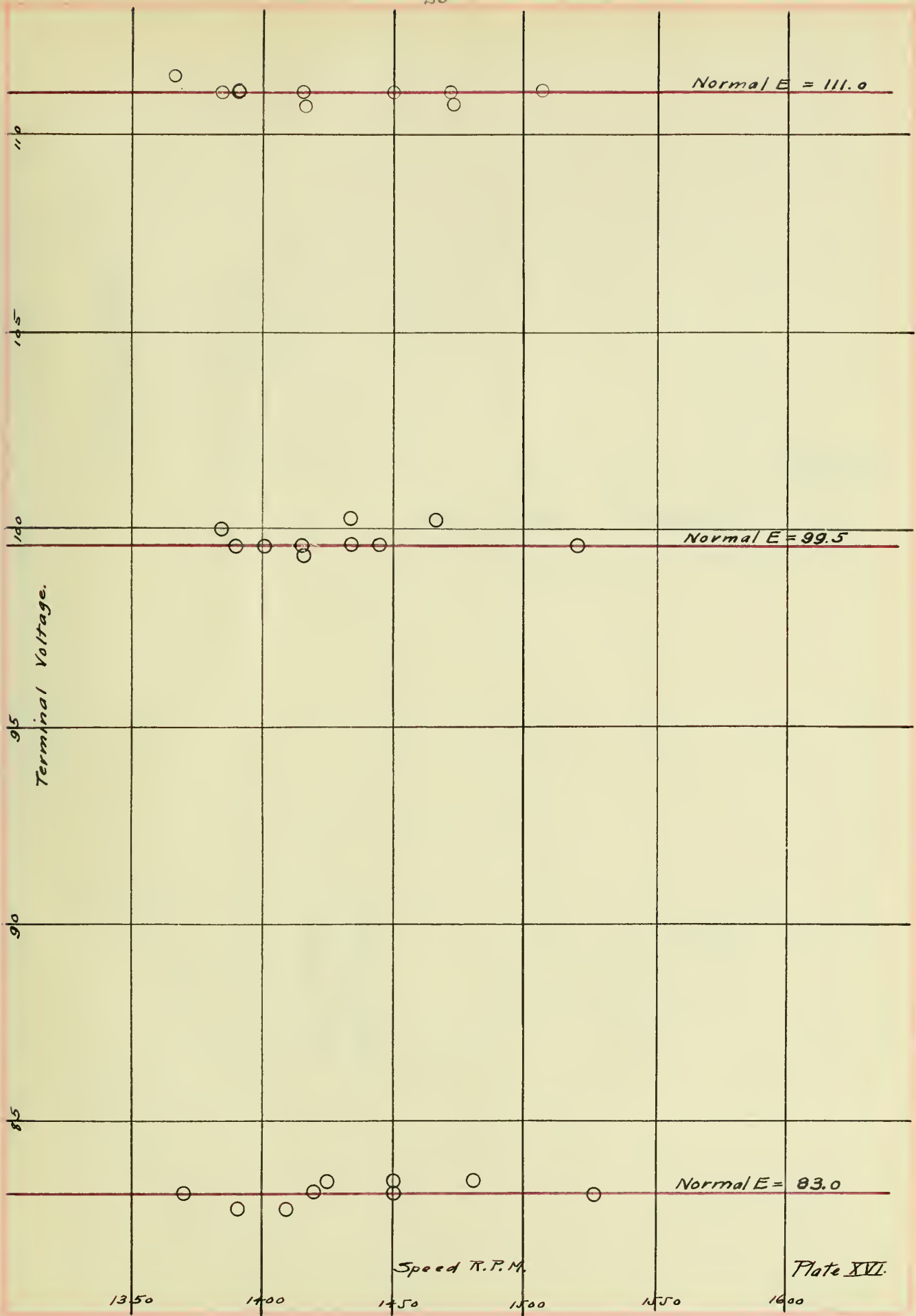


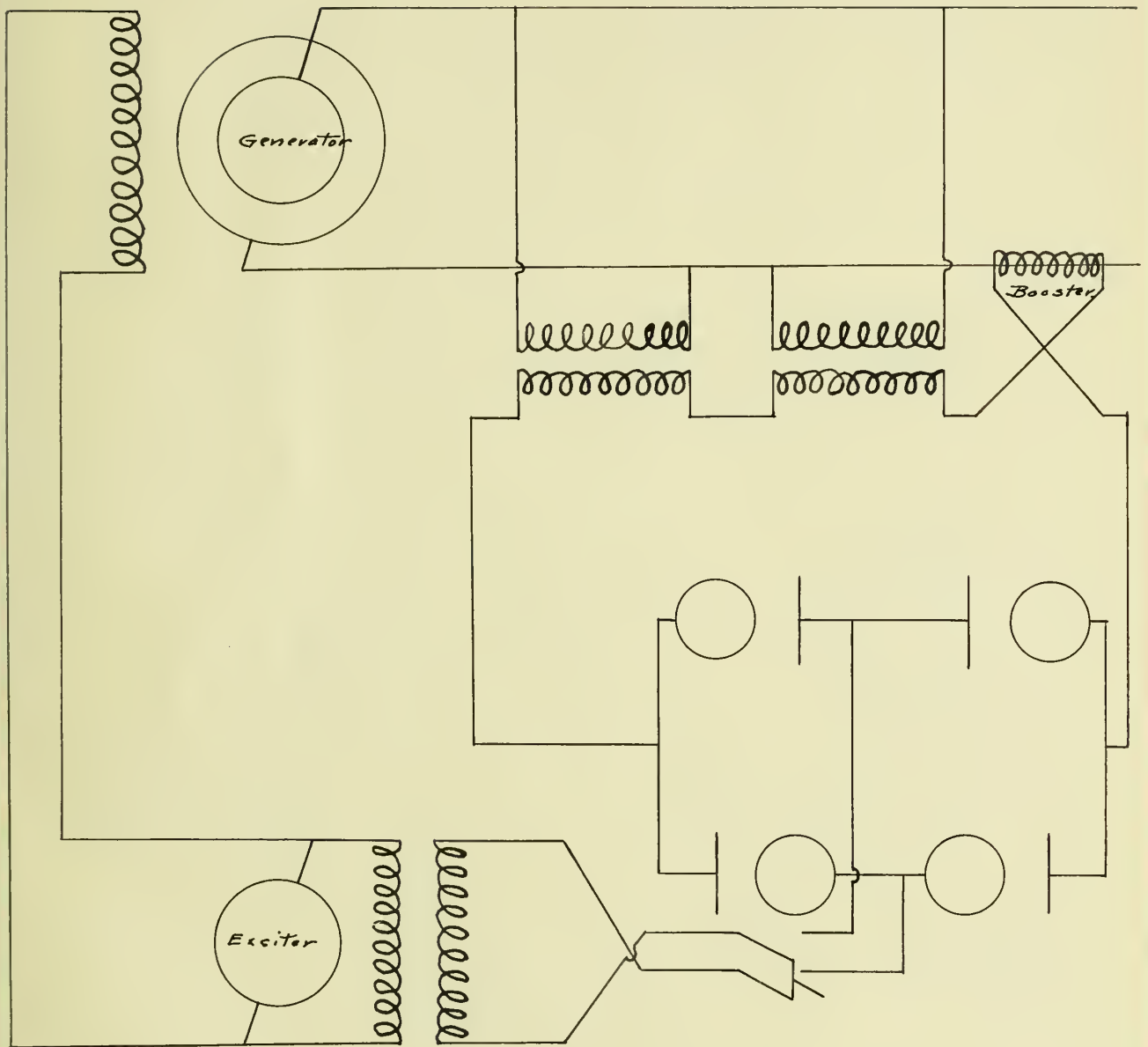
*Plate XI.**Plate XII.*



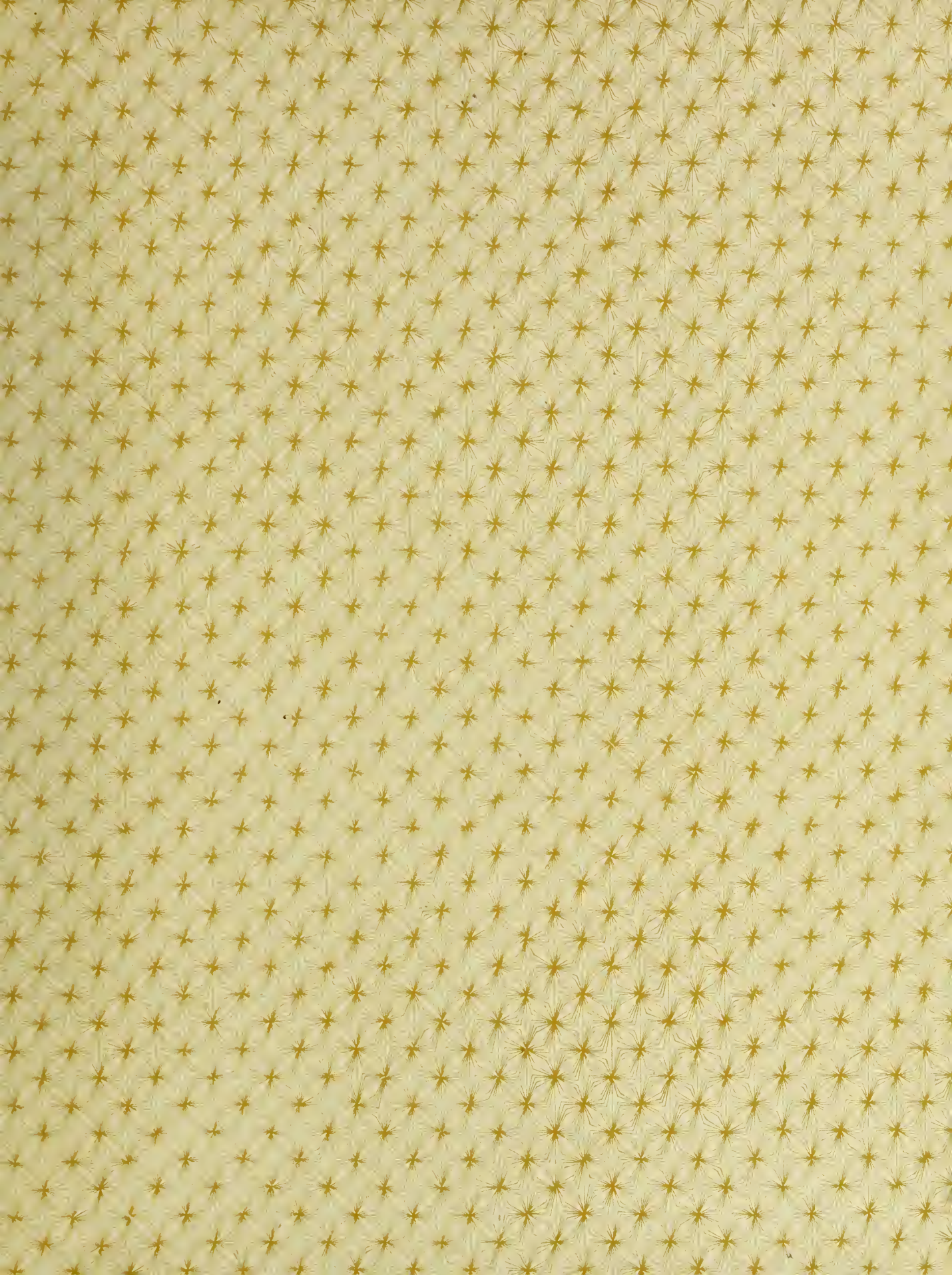












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